AIR FLUX DIRECTOR SYSTEM FOR X-RAY TUBES

The present application relates to the x-ray tube arts. The invention finds particular application in removing heat from a cooling liquid used to cool an x-ray tube and will be described with particular reference thereto. It will be appreciated, however, that the invention finds application in a variety of applications where it is desirable to transfer heat efficiently.

X-ray tubes typically include an evacuated envelope made of metal or glass, which is supported within an x-ray tube housing. The envelope houses a cathode assembly and an anode assembly. The cathode assembly includes a cathode filament through which a heating current is passed. This current heats the filament sufficiently that a cloud of electrons is emitted, i.e. thermionic emission occurs. A high potential, on the order of 100-200 kV, is applied between the cathode assembly and the anode assembly. The electron beam strikes the target with sufficient energy that x-rays and a large amount of heat are generated.

The x-ray tube housing surrounding the x-ray tube is filled with a fluid such as oil to aid in cooling the x-ray tube. In order to distribute the thermal loading created during the production of x-rays, a constant flow of cooling liquid is maintained throughout x-ray generation. After circulating through the x-ray tube housing, the cooling liquid is passed through a heat exchanger. The heat exchanger causes the heat stored in the oil to be radiated to the surrounding air, to transfer the heat by convection. The cooled oil is recirculated to the x-ray tube housing. A fan is typically used to direct air past or through the heat exchanger, to enhance heat transfer.

In computed tomography (CT) scanners, the x-ray tube and its associated heat exchanger and cooling fan are mounted to an annular rotating gantry. The gantry is rapidly

rotated around the patient to acquire a CT image. The weight of the heat exchanger and its associated fan play an important role in maintaining balance of the gantry during rotation. The size of the heat exchanger is also limited by the clearance constraints of the gantry. As thermal outputs of x-ray tubes increase, it is difficult for conventional fans to provide the high flow rates needed to maintain adequate cooling without being too heavy to achieve gantry balance. Additionally, larger fans tend to be noisy, which can disturb the patient.

The present invention provides a new and improved method and apparatus which overcome the above-referenced problems and others.

In accordance with one aspect of the present invention, a cooling system for use with an associated x-ray tube assembly is provided. The cooling system includes a heat exchanger which receives cooling fluid from a housing of the associated x-ray tube assembly and transfers heat between the cooling fluid and a flow of air. A fan is disposed to move the flow of air through the heat exchanger. An air flux director is positioned to intercept the flow of air from the heat exchanger and to redirect the flow of air in a direction which is generally perpendicular to an axis of rotation of the fan.

In accordance with another aspect of the invention, an x-ray tube assembly and cooling system is provided. The assembly includes an x-ray tube for generation of x-rays. A fluid flow path carries heated cooling fluid from the x-ray tube to a cooling system and returns cooled fluid to the x-ray tube. The cooling system includes an axial fan which is disposed to move a stream of air past a portion of the flow path, the fan having an axis of rotation. An air flux director is axially spaced from the fan and shaped to deflect air radially which has been exhausted by the fan.

In accordance with another aspect of the invention, a method for cooling an x-ray tube assembly is provided. The method includes receiving a heated cooling liquid from the x-ray tube through a fluid flow path. Heat is transferred between the cooling liquid and a flow of air generated by a fan. The fan exhausts the air flow in a direction generally parallel with its axis of rotation. The exhausted air is deflected in a direction which is generally perpendicular with the axial direction.

One advantage of at least one embodiment of the present invention is that it enables high cooling rates to be achieved without increasing the weight of a cooling system.

Another advantage of at least one embodiment of the present invention is that it allows more than one heat exchanger to operate side by side, thereby increasing the rate of cooling.

Another advantage of at least one embodiment of the present invention is that fan noise is reduced.

Another advantage of at least one embodiment of the present invention is that vibration is reduced.

Another advantage of at least one embodiment of the present invention resides in extend x-ray tube life.

Still further advantages of the present invention will become apparent to those of ordinary skill in the art upon reading and understanding the following detailed description of the preferred embodiments.

The invention may take form in various components and arrangements of components, and in various steps and arrangements of steps. The drawings are only for purposes of illustrating a preferred embodiment and are not to be construed as limiting the invention.

FIGURE 1 is a perspective view of an x-ray tube assembly and cooling system according to the present invention;

FIGURE 2 is diagrammatic illustration of the x-ray tube and the cooling system of FIGURE 1, partially cut away to reveal an anode assembly;

FIGURE 3 is an enlarged perspective view of the cooling system of FIGURE 1, with the fan cover removed for clarity;

FIGURE 4 is a schematic side sectional view of part of the cooling system of FIGURE 3;

FIGURE 5 is an enlarged perspective view of the air flux duct of FIGURE 3;

FIGURE 6 is an enlarged front perspective view of air flux director of FIGURE 3;

FIGURE 7 is a rear perspective view of the air flux director of FIGURE 6;

FIGURE 8 is a top view of the cooling system of FIGURE 3;

FIGURE 9 is a perspective view of part of the cooling system of FIGURE 3, showing a bracket for mounting the cooling system to the x-ray tube assembly of FIGURE 1;

FIGURE 10 is a perspective view of a CT scanner with the x-ray tube assembly and cooling system of FIGURE 1.

With reference to **FIGURE 1**, an x-ray tube assembly **10** of the type used in medical diagnostic systems, such as computed tomography (CT) scanners, for providing a beam of x-ray radiation is shown. The x-ray tube assembly **10** is cooled by a cooling system **12** including at least one a heat exchanger **14, 16**. Two heat exchangers **14, 16** are shown in the illustrated embodiment, arranged in parallel.

With reference now to **FIGURE 2**, the x-ray tube assembly **10** includes an anode assembly **20** which is rotatably mounted in an evacuated chamber **22**, defined by an envelope or frame **24**, typically formed from metal glass, and/or ceramic. The x-ray tube anode assembly **20** is mounted for rotation about an axis via a bearing assembly shown generally at **26**. A heated element cathode assembly **28** supplies and focuses

electrons. The cathode is biased, relative to the anode, such that the electrons are accelerated to the anode **20**. A portion of the electrons striking a target area of the anode is converted to heat and x-rays, which x-rays are emitted through a window **30** in the frame. The anode assembly **20**, cathode assembly **28**, and frame **24** together comprise an x-ray tube **32**.

The x-ray tube assembly **10** also includes a housing **40** filled with a heat transfer and electrically insulating cooling fluid, such as a dielectric oil. The housing **40** at least partly surrounds the frame **24** of the x-ray tube and defines a window **41** through which x-rays leave the x-ray tube assembly **10**. The cooling liquid is directed to flow past the window **30**, the frame **24**, bearing assembly **26**, and other heat-dissipating components of the x-ray tube **32**.

The cooling liquid is cooled by the cooling system **12**. Specifically, heated cooling liquid leaves the housing **40** through an outlet line **42**, located at the cathode end of the housing, is cooled by the cooling system, and the cooled liquid returns to the housing by a return line **44**, located at an anode end of the housing. The lines **42**, **44** may be in the form of flexible hoses, metal tubes, or the like and form part of a fluid flow path **46** which carries the cooling liquid through the heat exchangers **14**, **16** of the cooling system.

An accumulator **50** in the fluid flow path **46** accommodates changes in volume of the cooling liquid due to temperature fluctuations. The cooling liquid is pumped through the flow path **46** by a liquid pump **52**, which in the illustrated embodiment, is located in a fluid line **54**, intermediate the accumulator **50** and the heat exchangers **14**, **16**, although other locations are also contemplated. Downstream of the pump **52**, the cooling liquid is split into two lines **56**, **58**, one line going to each of the heat exchangers **14**, **16**. Within the respective heat exchanger **14**, **16**, the cooling liquid is directed along a convoluted radiator path, illustrated by tubing **60**, **62**, while air flowing through the heat exchanger contacts the tubing and is

heated thereby. The heat exchanger may include fins (not shown) for increasing the surface area for heat dissipation. In one embodiment, the heat exchanger is formed from aluminum or other lightweight material and has about 6 fins/cm. A heat exchanger of about 20 cm x 20 cm x 9 cm provides sufficient cooling capacity for an x-ray tube of about 4-6 KW power while meeting conventional gantry clearance constraints.

With reference now to **FIGURES 3** and **4**, cooling air from the surrounding environment enters the heat exchanger **14, 16** via a filter **70, 72**, mounted across an inlet port **74, 76** defined by a housing **77** of the respective heat exchanger **14, 16**. The filter **70, 72** can be of any conventional type, such as a foam. The density of the foam is preferably fine enough to catch dust that could inhibit the efficiency of the heat exchanger, but not so fine that it reduces the system's cooling efficiency. In one embodiment, a foam density of about 25 PPI is employed. The filter may be omitted if the design of the heat exchanger permits.

The air flow, heated by contact with the tubing **60, 62** and fins, exits the heat exchanger **14, 16** and enters a hollow air flux duct **78, 80**. The duct is mounted to the heat exchanger housing **77**, to surround an outlet port **82, 84** of the heat exchanger. The duct **78, 80**, forms a part of an air distribution system **86, 88** for the cooling system **12**.

It will be appreciated that the heat exchangers **14** and **16**, and their associated air distribution systems **86, 88** are identical, arranged as mirror images of each other. For convenience therefore, one of the air distribution systems **86** will be described in detail, with the understanding that the other air distribution system **88** operates analogously.

With particular reference to **FIGURE 4**, a cylindrical wall **89** of the air flux duct **78** is preferably formed of a fire retardant material, such as polycarbonate. The duct may have an axial length of about 4-8 cm and an internal diameter of about 16-26 cm.

With continued reference to **FIGURE 4**, the air distribution system **86** also includes a fan and motor assembly comprising a rotating fan **90**, driven by a fan motor **91**. The fan **90** is preferably an axial fan, although it is contemplated that a radial fan may be employed. Axial fans are those which direct the air flow in a generally axial direction, indicated by axis X-X, which is parallel with the rotational axis of the fan **90**. Air enters the fan in the same generally axial direction, via an inlet port **92** of the air flux duct **78**. A suitable fan **90** is one with a flow rate of about 15-20 m^3/min, or higher. For example, the fan may have five to ten blades or impellers **94** having an effective diameter of 15-25 cm and rotate at about 2800 rpm.

As illustrated in **FIGURE 4**, the blades **94** of the fan are located entirely within a cylindrically shaped internal passage **95** of the air flux duct **78**, adjacent a circular outlet port **96** of the duct. The duct **78** is sized, at its outlet end **96**, to provide a small clearance (e.g., about 0.02-0.1 cm) between the air flux duct and the fan blades **94**. In this way, an inner surface **98** of the air flux duct wall **89** helps to maintain the generally axial flow direction of the exhausted air.

As shown in **FIGURES 4** and **5**, the air flux duct **78** is mounted to the heat exchanger housing **77** with fixing members **100**, such as screws, bolts, or the like, which pass through suitably positioned apertures **102** (four in the illustrated embodiment) in a peripheral flange **104** at the inlet end **92** of the air flux duct. Adjacent the inlet end **92**, the air flux duct is widened, as necessary, to accommodate the size of the heat exchanger outlet port **82**. In the illustrated embodiment, molded corners **106** of the air flux duct are shaped to allow the duct inlet port **92** to closely match the rectangular shape of the heat exchanger outlet port **82**. The duct **78** thus provides a substantially airtight seal around the heat exchanger outlet port **82**. In this way, all or substantially all the air leaving the heat exchanger outlet **82** enters the air flux duct **78**.

The air exiting the outlet port **96** of the air flux duct **78** impinges on a contoured air flux director **110** which is axially aligned with and spaced from the outlet port. The air flux director intercepts the generally axial flow of air from the duct and directs the flow of air in a direction which is generally perpendicular to an axis of rotation of the fan **90** (i.e., the overall flow direction of the redirected air is closer to perpendicular than to axial). Specifically, the air flux director redirects the airflow through about 90° such that the air flows away from the air flux director in a generally lateral direction.

As best shown in **FIGURES 6** and **7**, the air flux director **110** includes a smoothly contoured disk or wall **112**, shaped like a truncated cone, with an outer surface **113** which curves inwardly. The disk increases in its outer diameter from a fan end **114** adjacent the fan **90** to an outer end **116**, furthest from the fan. In the illustrated embodiment the wall **112** is contoured with a radius of curvature **r** of, for example, about 8-10 cm in to reduce air constriction in the fan (**FIG. 4**). The outer diameter $\mathbf{d_d}$ at the outer end **116** is larger than the diameter $\mathbf{d_f}$ of the fan blades. For example, $\mathbf{d_d}$ may be about 100-120% of the diameter of the circle enscribed by the fan blades **94**. In the illustrated embodiment, $\mathbf{d_d}$ is 20-30 cm, or greater. At the fan end, the diameter is smaller than the outer diameter of the fan blades. The diameter at the fan end is governed, in part, by the size of the fan motor mounted thereon. By directing the airflow along a curved pathway, illustrated by the arrows in **FIGURE 4**, the air flux director reduces airflow noise which tends to result from turbulence.

The air flux director **110** is preferably formed of a fire retardant material, such as polycarbonate to keep its weight to a minimum and dampen vibration from the fan motor. The disk **112** may have a thickness of about 0.2-0.4 cm. Angularly spaced interior ribs **118** (eight ribs are illustrated in **FIG. 7**) are mounted to the disk **112** to help to maintain the rigidity of the air flux director **110**.

The flux director **110** defines an axially aligned socket **120** at the fan end, sized to receive the fan motor **91** therein. Apertures **122** (four in the illustrated embodiment) in the socket **120** receive fixing members **123** (**FIG. 4**), such as screws, bolts, or the like, for mounting the fan motor **91** to the air flux director **110**. Larger apertures **124, 126** are formed in the socket to receive wiring (not shown), portions of the motor, or the like. All of the apertures **122, 124, 126** are covered by the motor **91**, such that little or none of the cooling airflow from the fan passes through the air flux director **110**. As shown in **FIGURE 7**, the screws are axially aligned with the ribs **118** and carried by bores **128** of an annular support structure **129**, which, in combination with the ribs **118**, allows the air flux director **110** to be substantially hollow, and thus lightweight, while providing a rigid support for the motor **91**.

The air redirected by the air flux director **110** flows away from the heat exchangers though slots **130** milled in a cover **132** (**FIG. 1**) mounted over both air distribution systems **86, 88**. The slots **130** are sized and positioned to allow sufficient outward flow so as not to inhibit the efficiency of the cooling system.

To reduce turbulence resulting from interference of the flow patterns from the two parallel fan systems, an air flux separator **140** is mounted to the outer end of the air flux director. The separator **140** consists of a flat plate formed, for example aluminum sheet. Although two parallel flux separators **140, 141** are illustrated in **FIGURE 1**, one for each direction system **86, 88**, it is also contemplated that a single air flux separator could be used between the two systems. The air flux separator **140** is sufficiently large in area to minimize turbulence. The separator is of a larger size than the air flux director **110** and is generally square or rectangular in shape, rather than round. The separator **140** has apertures **142**, for receiving the motor mounting screws **123**, whereby the motor **91** and the air flux director **110** are mounted to the air flux separator.

Alternatively, instead of a flux separator **140**, the air flux director(s) could be formed with an outwardly extending flange (not shown) extending from its periphery.

As shown in **FIGURE 8** and **9**, fan mounting brackets **150**, **152** are attached to the heat exchangers **14**, **16**, respectively and serve as a base for the air flux director system **86**, **88**. Specifically, the brackets each include a plate **154**, which is mounted to the heat exchanger housing **77**, intermediate the air flux duct **78** and the heat exchanger, by the screws **100**. Clamps **156** extend from the plate **154** and are fixed at their distal ends to the rear of the air flux separator **140**. The bracket **150**, **152** defines an outwardly extending side flange **158** which is mounted to the x-ray tube housing by suitably positioned fixing members, such as screws **160** (**FIG. 1**). The bracket also includes axially extending top and bottom flanges **162** (only the top flange is visible), to which the cover **132** is mounted with suitable fixing members.

Heat dissipation is increased as compared to a system without a flux director. Increases in heat dissipation of 23% or more have been found, which render the cooling system **12** suitable for use with higher gantry speeds and/or higher output x-ray tubes than has conventionally been possible. For example heat dissipation rates of at least 130 Watts/°C, and generally, about 140-150 Watts/°C, or higher, are readily achieved with the present system, as compared to 108 Watts/°C with a conventional system.

As shown in **FIGURE 10**, the cooling system described has a suitable weight and size for use in a computed tomography (CT) system **200**. The CT system **200** includes an annular shaped gantry **210** which is rotatable about a gantry axis **Z**. The x-ray tube **10** and its associated cooling system **12** are mounted to the gantry. A patient support **212** is translated parallel to the **Z** axis though an examination region **214** within the gantry. x-rays passing through a subject **216** on the support are received by an arc of detectors **218** mounted to an opposite side of the gantry from

the x-ray tube assembly **10**. X-ray data representing a body structure of the subject is used to reconstruct an image of the body structure using an appropriate data processing and reconstruction system (not shown).

The axis of rotation **X** of the fans remains parallel to the axis of rotation **Z** of the gantry **210**. While the cooling system **12** has been described as being mounted to the x-ray tube housing **40** by brackets **150**, **152**, it is contemplated that the cooling system may alternatively be mounted to the gantry **210**.

Without intending to limit the scope of the invention, the following Example demonstrates the effectiveness of the cooling system.

Various cooling systems were constructed using either parallel paired radial fans or parallel paired axial fans of the type described previously. The axial fan (18.8 m^3/min flow rate at zero pressure drop, rotational speed 2,800 RPM, 20 cm blade diameter, with 9 blades) was supplied by the manufacturer with an outer frame (axial w/frame) formed of steel. The frame was removed in some tests prior to inserting the fan into the air flux duct (axial, no frame). Different types of filter were tested, including no filter, a 10 ppi filter, and a 25 ppi filter, the 10 ppi having larger holes and thus a less flow resistance than the 25 ppi filter. In these tests, the air flux duct was fairly crudely formed with a cylindrical shape (about 20 cm long), which did not completely cover the heat exchanger outlet. The air flux director was cut to shape, rather than molded (21 cm outer diameter, radius of curvature, 9.5 cm). In some tests, air flux separators were used, formed of aluminum sheet about 0.2 cm in thickness.

TABLE 1 shows the results obtained. Preferred configurations are generally those which have lower oil temperatures and higher heat dissipation rates (Q/ITD = rate/(hot oil temperature-cold oil temperature)). However, other factors, such as fan noise and tendency towards

vibration also tend to be important in assessing the suitability of the configuration for use in CT scanners.

The axial fan, without its manufacturers frame, performed well in the tests, particularly when combined with a duct, an air flux director, and air flux separator and a slotted cover. Test 13, for example has a heat dissipation rate of 132 Watts/°C, which compares very favorably with a conventional heat exchanger design having a heat dissipation rate of 108 W/°C. This arrangement also had low noise output and reduced vibration, as compared with conventional fans.

Tests similar to those described for EXAMPLE 1 were carried out with a cooling system comprising 2 heat exchangers, 2 axial fans, 2 ducts, 2 air flux directors, and 2 separators. In these tests, the air flux duct was molded to provide corner pieces as shown in **FIGURE 5** to allow the air flux duct to more closely match the shape of the heat exchanger outlet. The duct outlet diameter was designed to be closer to that of the fan blades than in EXAMPLE 1, allowing the fan to operate more efficiently. The flux director was also increased in size, from about a 21 cm maximum diameter to a 24.6 cm maximum diameter and molded to provide a smoother outer surface than the rough cut director used in EXAMPLE 1. These changes were found to reduce air flow friction and turbulence so that heat dissipation efficiency was improved. The heat dissipation results (Q/ITD) are shown in TABLE 2 and compared with those for a commercial cooling system operating with radial fans. For each test, the power to the anode, stator, and pump was the same (4500 W, 400 W, and 187 W, respectively). The heat dissipation from the x-ray tube housing was therefore the same for each configuration (350W). Predicted maximum cooling oil temperatures were based on a gantry temperature of 37°C.

TABLE 2

Configuration	Q/ITD, W/°C	Predicted maximum cooling oil temperature, °C
Commercial cooling system (with radial fan)	126	73
Cooling system with axial fan, duct, air flux director, and air flux separator	150	67

As can be seen from TABLE 2, the present cooling system outperformed the commercial cooling system in terms of heat dissipation rate. The maximum cooling oil temperature was also significantly lower for the present system than for the commercial system. Based on the results obtained, the present cooling system is capable of maintaining very effective cooling of an x-ray tube operating at a power of at least 4.5 KW by maintaining the oil temperature at less than 63°C. If the oil temperature is allowed to be slightly higher, the cooling system is expected be able to maintain effective cooling of an x-ray tube which operates at about 6 KW, which is much higher than current commercial cooling systems are able to handle.

The invention has been described with reference to the preferred embodiment. Modifications and alterations will occur to others upon a reading and understanding of the preceding detailed description. It is intended that the invention be construed as including all such modifications and alterations insofar as they come within the scope of the appended claims or the equivalents thereof.

TABLE 1

Test	Fan	Air Flux Separ-ator	Air Flux Duct	Air Flux Director	Air Filter, PPI	Fan Weight, lb (one side)	Cover	Highest Oil Temp, °C	Q/ITD, W/C
1	Radial	No	No	No	25	3.5	Yes	63	134
2	Axial, no frame	Yes	No	Yes	25	3.8	Yes	65.4	100.22
3	Axial, no frame	Yes	No	Yes	25	3.9	Yes	63.3	105.5
4	Axial, w/frame	Yes	No	No	25	4.7	Yes	68	108
5	Axial, w/frame	Yes	No	No	25	4.7	No	63.4	125.2
6	Axial, w/frame	Yes	No	No	25	4.7	Yes	69	109.8
7	Axial, w/frame	Yes	No	No	25	4.7	No	67.0	108
8	Axial, w/frame	Yes	No	No	25	4.7	No	63.0	125
9	Axial, w/frame	Yes	No	No	None	4.7	No	59.5	142.5
10	Axial, w/frame	Yes	No	No	None	4.7	Slotted cover	63	127
11	Axial, no frame	Yes	Yes	Yes	None	4.2	Slotted cover	63	145
12	Axial, no frame	Yes	Yes	Yes	10	4.2	Slotted cover	63.2	133
13	Axial, no frame	Yes	Yes	Yes	25	4.2	Slotted Cover	62.6	132